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# NOTE ON REALIZATION OF CUSP CROSS-SECTIONS OF COMPLEX HYPERBOLIC ORBIFOLDS

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## INTRODUCTION

Long and Reid [3] has shown that every flat manifold of dimension  $n \geq 3$  arises as some cusp cross-section of a finite volume cusped (real) hyperbolic orbifold. McReynolds has proved that every 3-dimensional infranil manifold is a cusp of a complex hyperbolic 2-orbifold. Long and Reid [4] has also proved that some compact flat 3-manifold cannot be a cusp cross-section of a 1-cusped finite volume hyperbolic manifold. In this note we give a negative answer similarly to the flat case.

**Theorem 1.** *There exists a 3-dimensional closed Heisenberg infranilmanifold which cannot be a cusp cross-section of a 1-cusped finite volume complex hyperbolic 2-manifold.*

## 1. HEISENBERG LIE GROUPS

Let  $\mathbf{K}$  be the field of real numbers  $\mathbb{R}$ , complex numbers  $\mathbb{C}$  respectively. Denote  $c = 1, 2$  according to  $\mathbb{R}, \mathbb{C}$ . We define the bilinear form  $Q$  on the  $\mathbf{K}$ -vector space  $\mathbf{K}^{n+2}$ :

$$Q(z, w) = -\bar{z}_1 w_1 + \bar{z}_2 w_2 + \cdots + \bar{z}_{n+2} w_{n+2}.$$

Let  $P : \mathbf{K}^{n+2} - \{0\} \rightarrow \mathbf{K}\mathbb{P}^{n+1}$  be the projection onto the  $c(n+1)$ -dimensional  $\mathbf{K}$ -projective space respectively.

When  $\mathrm{GL}(n+2, \mathbf{K})$  is the group of all invertible  $(n+2) \times (n+2)$ -matrices with entries in  $\mathbf{K}$ , the  $\mathbf{K}$ -Lorentz group  $\mathrm{O}(n+1, 1; \mathbf{K})$  is defined to be the subgroup  $\{A \in \mathrm{GL}(n+2, \mathbf{K}) \mid Q(Az, Aw) = Q(z, w) \forall z, w \in \mathbf{K}^{n+2}\}$ . The kernel of this action is the center  $C(\mathbf{K})$  isomorphic to  $\{\pm 1\}$  if  $\mathbf{K} = \mathbb{R}$  or the circle  $S^1$  if  $\mathbf{K} = \mathbb{C}$ . Let  $\mathrm{PO}(n+1, 1; \mathbf{K})$  be the quotient group  $\mathrm{O}(n+1, 1; \mathbf{K})/C(\mathbf{K})$ . It is customary to write  $\mathrm{PO}(n+1, 1; \mathbf{K})$  as  $\mathrm{PO}(n+1, 1)$ ,  $\mathrm{PU}(n+1, 1)$  respectively. If we choose the quadratic space  $V_0^{c(n+2)-1} = \{z \in \mathbf{K}^{n+2} - \{0\} \mid Q(z, z) = 0\}$ ,

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then  $P(V_0^{c(n+2)-1})$  is the  $(c(n+1) - 1)$ -dimensional sphere  $S^{c(n+1)-1}$  in  $\mathbf{K}\mathbb{P}^{n+1}$ . As the group  $\mathrm{PO}(n+1, 1; \mathbf{K})$  leaves  $S^{c(n+1)-1}$  invariant and transitive. This gives the geometry  $(\mathrm{PO}(n+1, 1; \mathbf{K}), S^{c(n+1)-1})$ . According to whether  $\mathbf{K} = \mathbb{R}, \mathbb{C}$ , we get the conformally flat geometry,  $(\mathrm{PO}(n+1, 1), S^n)$ , the spherical  $CR$  geometry  $(\mathrm{PU}(n+1, 1), S^{2n+1})$ . The imaginary part of  $\mathbb{C}$ ,  $\mathrm{Im}\mathbb{C}$  is the real vector space  $\mathbb{R}$ . (In addition,  $\mathrm{Im}\mathbb{R} = 0$ .)

The  $\mathbf{K}$ -Heisenberg nilpotent Lie group  $\mathcal{N}_{\mathbf{K}}$  is the the product  $\mathrm{Im}\mathbf{K} \times \mathbf{K}^n$  with group law:

$$(1.1) \quad (a, z) \cdot (b, w) = (a + b - \mathrm{Im}\langle z, w \rangle, z + w),$$

where the Hermitian inner product  $\langle \cdot, \cdot \rangle$  on  $\mathbf{K}^n$  is defined as

$$\langle z, w \rangle = \bar{z}_1 \cdot w_1 + \bar{z}_2 \cdot w_2 + \cdots + \bar{z}_n \cdot w_n.$$

Here  $\bar{z}$  is the complex conjugate of  $z$ . It is easy to see that  $\mathcal{N}_{\mathbf{K}}$  is 2-step nilpotent, i.e.  $[\mathcal{N}_{\mathbf{K}}, \mathcal{N}_{\mathbf{K}}] = (\mathrm{Im}\mathbf{K}, 0)$ . Identified  $(\mathrm{Im}\mathbf{K}, 0)$  with  $\mathrm{Im}\mathbf{K}$ , it is the central subgroup  $\mathcal{C}(\mathcal{N}_{\mathbf{K}})$  of  $\mathcal{N}_{\mathbf{K}}$ . This induces a canonical central group extension:

$$(1.2) \quad 1 \rightarrow \mathcal{C}(\mathcal{N}_{\mathbf{K}}) \rightarrow \mathcal{N}_{\mathbf{K}} \xrightarrow{P} \mathbf{K}^n \rightarrow 1.$$

According to whether  $\mathbf{K} = \mathbb{R}, \mathbb{C}$ ,  $\mathcal{N}_{\mathbf{K}}$  is described as the vector space  $\mathbb{R}^n$ , and the Heisenberg nilpotent Lie group  $\mathcal{N}$ . Each space  $\mathbb{R}^n$ ,  $\mathcal{N}$  has the conformally flat structure, spherical  $CR$  structure respectively. Let  $\mathrm{Sim}(\mathcal{N}_{\mathbf{K}})$  be the subgroup of the automorphism group  $\mathrm{Aut}(\mathcal{N}_{\mathbf{K}})$  whose elements preserve the geometric structure on  $\mathcal{N}_{\mathbf{K}}$  respectively. Then  $\mathrm{Sim}(\mathcal{N}_{\mathbf{K}})$  is isomorphic to the semidirect product  $\mathbb{R}^n \rtimes (\mathrm{O}(n) \times \mathbb{R}^+)$ ,  $\mathcal{N} \rtimes (\mathrm{U}(n) \times \mathbb{R}^+)$  respectively. Note that  $\mathrm{Sim}(\mathcal{N}_{\mathbf{K}})$  for  $\mathbf{K} = \mathbb{C}$  are called generalized similarity transformations generated by translations, rotations and similarities in the sense of each geometry. Obviously as  $\mathrm{Sim}(\mathcal{N}_{\mathbf{K}})$  acts transitively on  $\mathcal{N}_{\mathbf{K}}$ , we arrive at the  $\mathbf{K}$ -Heisenberg geometry:  $(\mathrm{Sim}(\mathbb{R}^n), \mathbb{R}^n)$ ,  $(\mathrm{Sim}(\mathcal{N}), \mathcal{N})$ . Note that the group  $\mathrm{Sim}(\mathcal{N}_{\mathbf{K}})$  acts on  $\mathcal{N}_{\mathbf{K}}$  as follows:  $(x \in \mathbb{R}^n, (b, v) \in \mathcal{N} = \mathbb{R} \times \mathbb{C}^n)$ :

$$(1.3) \quad \begin{aligned} &\text{If } (z, (A, t)) \in \mathbb{R}^n \rtimes (\mathrm{O}(n) \times \mathbb{R}^+), \\ &\quad ((z, (A, t)) \cdot x = z + t \cdot Ax. \\ &\text{If } ((a, z), (A, t)) \in \mathcal{N} \rtimes (\mathrm{U}(n) \times \mathbb{R}^+), \\ &\quad ((a, z), A, t) \cdot (b, v) = (a + t^2 \cdot b, t \cdot Av). \end{aligned}$$

Letting  $\mathrm{O}(n, \mathbf{K}) = \mathrm{O}(n), \mathrm{U}(n)$  respectively, we write the above group  $\mathrm{Sim}(\mathcal{N}_{\mathbf{K}}) = \mathcal{N}_{\mathbf{K}} \rtimes (\mathrm{O}(n, \mathbf{K}) \times \mathbb{R}^+)$ .

On the other hand, we observe that  $\mathrm{Sim}(\mathcal{N}_{\mathbf{K}})$  is realized as the maximal amenable Lie subgroup of  $\mathrm{PO}(n+1, 1; \mathbf{K}), S^{c(n+1)-1}$ . Choose the

standard basis  $\{e_1, \dots, e_{n+2}\}$  of  $\mathbf{K}^{n+2}$  with respect to the Hermitian form  $Q$  for which  $Q(e_1, e_1) = -1, Q(e_i, e_j) = \delta_{ij}$  ( $i, j = 2, \dots, n+2$ ),  $Q(e_1, e_j) = 0$  ( $j = 2, \dots, n+2$ ).

Let  $P : (\mathbf{O}(n+1, 1; \mathbf{K}), V_0^{c(n+2)-1}) \rightarrow (\mathbf{PO}(n+1, 1; \mathbf{K}), S^{c(n+1)-1})$  be the equivariant projection as before.

If we put  $f_1 = (e_1 + e_{n+2})/\sqrt{2}, f_{n+2} = (e_1 - e_{n+2})/\sqrt{2}$  respectively, then the vectors  $f_1, f_{n+2}$  lie in the cone  $V_0^{c(n+2)-1}$  of  $\mathbf{K}^{n+2}$ . We call  $P(f_1) = \infty$  the point at infinity (north pole) in  $S^{c(n+1)-1}$ . (Similarly,  $P(f_{n+2}) = 0$  the origin (south pole) of  $S^{c(n+1)-1}$ .) The stabilizer at  $\{\infty\}$  of the isometry group  $\text{Iso}(\mathbb{H}_{\mathbf{K}}^{n+1})$  is isomorphic to  $\mathbf{PO}(n+1, 1; \mathbf{K})_{\infty} \rtimes \langle \tau \rangle$ , where  $\tau$  is the identity,  $\mathbf{K} = \mathbb{R}$  or the involution,  $\mathbf{K} = \mathbb{C}$ . The geometry  $(\mathbf{PO}(n+1, 1; \mathbf{K}), S^{c(n+1)-1})$  restricts the geometry  $(\mathbf{PO}(n+1, 1; \mathbf{K})_{\infty}, S^{c(n+1)-1} - \{\infty\})$  which is isomorphic to the  $\mathbf{K}$ -Heisenberg geometry  $(\text{Sim}(\mathcal{N}_{\mathbf{K}}), \mathcal{N}_{\mathbf{K}})$ . Moreover we observe how  $\text{Sim}(\mathcal{N}_{\mathbf{K}})$  is realized as the stabilizer of  $\mathbf{PO}(n+1, 1; \mathbf{K})$  at  $\infty$  under the identification  $\mathcal{N}_{\mathbf{K}} = S^{c(n+1)-1} - \{\infty\}$ . First note that if  $G$  is a subgroup of  $\mathbf{PO}(n+1, 1; \mathbf{K})$  which leaves  $f_1$  invariant, then  $PG$  is isomorphic to  $\mathbf{PO}(n+1, 1; \mathbf{K})_{\infty}$ . Now each element  $g$  of  $G$  has the following form with respect to the basis  $\{f_1, e_2, \dots, e_{n+1}, f_{n+2}\}$ :

$$g = \begin{pmatrix} \lambda & \lambda^t \bar{y} B & z \\ 0 & B & y \\ 0 & 0 & \mu \end{pmatrix}$$

satisfying that

- (1)  $\lambda, \mu \in \mathbf{K}^*$  with  $\bar{\lambda}\mu = 1$ .
- (2)  $B$  is a matrix contained in  $\mathbf{O}(n), \mathbf{U}(n)$  respectively.
- (3)  $y$  is an  $n$ -th column vector, and  $z \in \mathbf{K}$  with  $\bar{z}\mu + \bar{\mu}z = |y|^2$ .

Then  $\mathbf{K}$ -Heisenberg Lie group  $\mathcal{N}_{\mathbf{K}}$  is the subgroup consisting of the following matrices for  $\mathbf{K} = \mathbb{R}, \mathbb{C}, \mathbb{H}$  respectively;

$$\begin{pmatrix} 1 & {}^t \bar{y} & \frac{|y|^2}{2} \\ 0 & I & y \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & {}^t \bar{y} & \frac{|y|^2}{2} - \mathbf{i}a \\ 0 & I & y \\ 0 & 0 & 1 \end{pmatrix}.$$

It can be checked that the correspondence

$$(1.4) \quad \begin{pmatrix} \lambda & \lambda^t \bar{y} B & z \\ 0 & B & y \\ 0 & 0 & \mu \end{pmatrix} \mapsto ((-\text{Im}(z\bar{\lambda}), y\bar{\lambda}), (B, \lambda))$$

is an isomorphism of  $G$  onto  $\mathbb{R}^n \rtimes (\mathbf{O}(n) \times \mathbb{R}^*)$  (respectively  $\mathcal{N} \rtimes (\mathbf{U}(n) \times \mathbb{C}^*)$ .) As the center  $\mathcal{C}(\mathbf{K}) = \{\pm 1\}, S^1, \{\pm 1\}$  respectively, this induces an isomorphism from  $PG = \mathbf{PO}(n+1, 1; \mathbf{K})_{\infty}$  onto  $\text{Sim}(\mathcal{N}_{\mathbf{K}}) = \mathcal{N}_{\mathbf{K}} \rtimes (\mathbf{O}(n, \mathbf{K}) \times \mathbb{R}^+)$  respectively. Denote the group of rigid motions of  $\mathcal{N}_{\mathbf{K}}$

by  $E(\mathcal{N}_{\mathbf{K}}) = \mathcal{N}_{\mathbf{K}} \rtimes O(n, \mathbf{K})$ . Form the group  $E^\tau(\mathcal{N}_{\mathbf{K}}) = E(\mathcal{N}_{\mathbf{K}}) \rtimes \langle \tau \rangle$  which is a subgroup of  $\text{Iso}(\mathbb{H}_{\mathbf{K}}^{n+1})_\infty$ .

**Definition 1.1.** We call  $E^\tau(\mathcal{N}_{\mathbf{K}})$  the  $\mathbf{K}$ -Heisenberg euclidean group. A generalized  $\mathbf{K}$ -Heisenberg infranilmanifold (orbifold) is a compact manifold (orbifold)  $\mathcal{N}_{\mathbf{K}}/\Gamma$  such that  $\Gamma$  is a (torsion free) discrete cocompact subgroup of  $E^\tau(\mathcal{N}_{\mathbf{K}})$ . In addition, if  $\Gamma$  belongs to  $E(\mathcal{N}_{\mathbf{K}})$ , then  $\mathcal{N}_{\mathbf{K}}/\Gamma$  is called a  $\mathbf{K}$ -Heisenberg infranilmanifold.

Given a noncompact finite volume hyperbolic manifold  $\mathbb{H}_{\mathbf{K}}^{n+1}/G$ , the form of a cusp-cross section is described as a generalized  $\mathbf{K}$ -Heisenberg infranilmanifold:

$$(1.5) \quad \mathcal{N}_{\mathbf{K}}/\Gamma \text{ where } G_\infty = \Gamma \subset E^\tau(\mathcal{N}_{\mathbf{K}}).$$

An automorphism  $h$  of the  $\mathbf{K}$ -Heisenberg euclidean group  $E^\tau(\mathcal{N}_{\mathbf{K}})$  is defined by  $h = (h_0, \hat{h}) : \mathcal{N}_{\mathbf{K}} \rightarrow \mathcal{N}_{\mathbf{K}}$ , more precisely  $h \in O(n)$ ,  $h = (1, \hat{h}) \in U(n)$ . The group  $E^\tau(\mathcal{N}_{\mathbf{K}})$  acts on  $\mathcal{N}_{\mathbf{K}}$  as follows (see (1.3)): if  $(b, w) \in \mathcal{N}_{\mathbf{K}}$ ,

$$\begin{aligned} ((a, z), h) \cdot (b, w) &= (a, z) \cdot h(b, w) = (a, z) \cdot (h_0(b), \hat{h}(w)) \\ &= ((a + h_0(b) - \text{Im}\langle z, \hat{h}(w) \rangle), z + \hat{h}(w)) \end{aligned}$$

We can define a map  $\Psi_\theta : E^\tau(\mathcal{N}_{\mathbf{K}}) \rightarrow E^\tau(\mathcal{N}_{\mathbf{K}})$  for each real nonzero number  $\theta$ :

$$(1.6) \quad \Psi_\theta((a, z), h) = ((\theta^2 \cdot a, \theta \cdot z), h)$$

for  $(a, z) \in \mathcal{N}_{\mathbf{K}}$ ,  $h \in O(n, \mathbf{K}) \rtimes \langle \tau \rangle$ .

As  $((a, z), h)((b, w), g) = ((a + h(b) - \text{Im}\langle z, h(w) \rangle), h \circ g)$ , it is easy to see that  $\Psi_\theta$  is an isomorphism of  $E^\tau(\mathcal{N}_{\mathbf{K}})$  onto itself.

## 2. GEOMETRIC BOUNDARY

We shall consider whether every Heisenberg infranilmanifold can be arised, up to diffeomorphism, as a cusp cross-section of a complete finite volume 1- cusped complex hyperbolic manifold. In [1], Burns and Epstein has obtained the  $CR$ -invariant  $\mu(M)$  on the 3-dimensional strictly pseudoconvex  $CR$ -manifolds  $M$  provided that the holomorphic line bundle is trivial. Let  $N$  be a compact strictly pseudoconvex complex 2-dimensional manifold with smooth boundary  $M$ . Then they have shown the following equality in [2]:

$$(2.1) \quad \int_N c_2 - \frac{1}{3}c_1^2 = \chi(N) - \frac{1}{3} \int_N \bar{c}_1^2 + \mu(M).$$

Here  $\bar{c}_1$  is a lift of  $c_1$  by the inclusion  $j^* : H^2(N, M : \mathbb{R}) \rightarrow H^2(N : \mathbb{R})$ .

Let  $E^\tau(\mathcal{N}) = \mathcal{N} \rtimes U(1)$  be the 3-dimensional  $\mathbb{C}$ -Heisenberg euclidean group (cf. 1.1). Let  $L : E^\tau(\mathcal{N}) \rightarrow U(1)$  be the holonomy homomorphism.

**Theorem 2.1.** *There exists a 3-dimensional infranilmanifold  $\mathcal{N}/\Gamma$  which does not bound a complete complex hyperbolic 2-manifold (no cusp cross-section of one cusped complex hyperbolic manifold).*

*Proof.* There exists a 3-dimensional Heisenberg infranilmanifold  $M = \mathcal{N}/\Gamma$  but not a homogeneous space and the holonomy group  $L(\Gamma)$  is odd cyclic (see [5] for the classification. ) Suppose that  $M$  is realized as a cusp-cross section of a complete finite volume one-cusped complex hyperbolic manifold  $W = \mathbb{H}_{\mathbb{C}}^2/\pi$ . Then we view  $M$  as a boundary of  $\tilde{W}$  where  $\tilde{W} \setminus \partial\tilde{W}$  supports a complete complex hyperbolic structure. The spherical  $CR$ -structure on  $M$  is induced from the complex hyperbolic structure on  $W$ . Let  $p : \tilde{\tilde{W}} \rightarrow \tilde{W}$  be the finite cover, say of order  $\ell$ , whose induced covering  $\tilde{M}$  of  $M$  is now a nilmanifold (possibly consists of a finite number of such manifolds). We may assume  $\ell$  is odd prime (see [5]). Since  $W$  admits a complete Einstein-Kähler metric, we know that  $c_2 - \frac{1}{3}c_1^2 = 0$ . Moreover, since  $\tilde{M}$  is a spherical  $CR$  manifold with trivial holomorphic line bundle, it follows that  $\mu(\tilde{M}) = 0$ . Applying the above equality to  $\tilde{\tilde{W}}$ , we have  $\chi(\tilde{\tilde{W}}) = \frac{1}{3} \int_{\tilde{\tilde{W}}} \bar{c}_1^2$ . As  $p^*(\bar{c}_1(W)) = \bar{c}_1(\tilde{\tilde{W}})$  by naturality and  $p_*[\tilde{\tilde{W}}] = \ell[W]$ ,

$$(2.2) \quad \int_{\tilde{\tilde{W}}} \bar{c}_1^2 = \langle \bar{c}_1^2(\tilde{\tilde{W}}), [\tilde{\tilde{W}}] \rangle = \langle \bar{c}_1^2(W), \ell[W] \rangle.$$

Since  $\chi(\tilde{\tilde{W}}) = \ell\chi(W)$ , it follows that

$$(2.3) \quad 3\chi(W) = \langle \bar{c}_1^2(W), [W] \rangle.$$

As a consequence,  $\bar{c}_1(W)$  could be an integer, i.e.  $\bar{c}_1(W) \in H^2(W, \mathbb{N} : \mathbb{Z})$  so that  $j^*\bar{c}_1(W) = c_1(W) \in H^2(W : \mathbb{Z})$ .

On the other hand, given a  $CR$  structure on  $M$ , there is the canonical splitting  $TM \otimes \mathbb{C} = B^{1,0} \oplus B^{0,1}$  where  $B^{1,0}$  is the holomorphic line bundle. Since  $M$  is an infranilmanifold but not homogeneous,  $B^{1,0}$  is nontrivial, i.e.  $c_1(B^{1,0}) \neq 0$ . (In fact, it is a torsion element in  $H^2(N : \mathbb{Z})$ , because the  $\ell$ -fold covering  $\tilde{M}$  has the trivial holomorphic bundle.) The spherical  $CR$  manifold  $M$  has a characteristic  $CR$  vector field (Reeb field)  $\xi$ . If  $\epsilon^1$  is the vector field on  $M$  pointing outward to  $W$ , then the vector fields  $\langle \epsilon^1, \xi \rangle$  generates a trivial holomorphic line bundle  $TC$  on  $M$  for which  $TW \otimes \mathbb{C}|_M = B^{1,0} + TC^{1,0} \oplus B^{0,1} + TC^{0,1}$ . In

particular,

$$0 = i^* j^*(\bar{c}_1(W)) = i^* c_1(W) = c_1(B^{1,0} + T\mathbb{C}^{1,0}) = c_1(B^{1,0}),$$

which is a contradiction. □

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